PRAMANA
— journal of
physics

© Printed in India

Supplement to Vol. 41
December 1993
pp. 441–453

Cosmology after COBE—review for particle physicists

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Abstract. I summarize the following current topics in cosmology: (1) The near-success of Cold Dark Matter (CDM) in predicting the COBE fluctuation amplitude, which favors the hypothesis that structure formed in the universe through gravitational collapse. (2) The indications that $\Omega \approx 1$ and that the power spectrum has a little more power on supercluster and larger scales than CDM. These are suggested by the IRAS and CfA redshift surveys and POTENT galaxy peculiar velocity analysis, and also by the COBE data. (3) The consequent demise of CDM and the rise of hybrid schemes such as Cold+Hot Dark Matter (C+HDM). (4) The possible implications for neutrino masses and mixings, and for cosmology, of the recent results on solar neutrinos. (5) CERN experiments on ν_μ-ν_τ oscillations, which may be sufficiently sensitive to detect the ν_τ if its mass lies in the cosmologically interesting mass range 1-10^2 eV. (6) Dark matter searches, including the searches for WIMPs and axions, and the French, Polish, and Berkeley-Livermore-Mt. Stromlo MACHO searchs.

1. Introduction

The goal of Particle Astrophysics is to construct a fundamental theory of the material universe—i.e., to explain elegantly and economically observations from the smallest physical scale to the entire cosmological horizon. Of course, science can never tell us which theories are "true"; at best it can only tell us which are false. Paradoxically, the theories that most closely approach truth are those whose limits are *known*, like Newtonian Mechanics. We know where Newtonian Mechanics is valid because we know precisely where and how it fails, since it is enveloped on all sides by more accurate theories: Quantum Mechanics for small sizes, Special Relativity for high speeds, General Relativity for large size or large gravitational potential $\phi \sim m/r$. [1]. It has even been possible to combine some of these theories, as in QED. But we do not know where or how these theories in turn fail. So our goal is to construct enveloping theories for them.

In particular, in particle physics our goal is to construct an enveloping theory for the 3-2-1 "Standard Model," based on the $SU(3)_c \times [SU(2) \times U(1)]_{ew}$ gauge group for three generations of quarks and leptons, with all three neutrinos massless. A century ago, there were only a few "clouds on the horizon" portending the storms that destroyed classical physics. Perhaps the main cloud now on the horizon of the particle physics Standard Model is the hint of neutrino mass from the solar neutrino data, which I will summarise in §4.

In cosmology, we do not yet even have a fundamental theory. Cosmology today is like physics before Newtonian Mechanics or geology before Plate Tectonics. We only have bits and pieces of the story. Perhaps standard Big Bang Nucleosynthesis is such a piece. Almost certainly General Relativity is. Cold Dark Matter (CDM) was an educated guess regarding such a fundamental theory. But, like the original SU(5) Grand Unified Theory in particle physics, CDM was apparently too simple to be true, as I will summarize in §2-3. In constructing a fundamental theory of cosmology, it now appears that the data requires a hybrid theory containing elements of at least two simpler theories, such as Cold + Hot Dark Matter (C+HDM; see §3). The resulting theory may thus be a little like the 3-2-1 standard model of particle physics, which is of course also a hybrid theory. Another possibly useful analogy is elliptical planetary orbits. For millennia, until Kepler and Newton, astronomical prejudice favored circles; now we know that only an unusual accident of planetary formation would give truly circular orbits (i.e., very small ellipticity).

2. Cold dark matter

In saying that the data do not favor the original CDM theory, I do not mean to imply that there is any evidence against all or most of the dark matter being of the "cold" variety, such as weakly interacting massive particles (WIMPs) or axions. I propose to use capital letters CDM (Cold Dark Matter) to refer to the "standard CDM" theory based not only on the assumption that the dark matter is cold, but also on the assumptions that structure in the universe grew gravitationally from Gaussian adiabatic fluctuations with a Zel'dovich spectrum in a universe of critical density ($\Omega = 1$). These latter assumptions are of course just what the simplest versions of inflation imply [2].

With CDM, the primordial Zel'dovich ($|\delta_k|^2 \propto k^n$ spectrum with $n = 1$) is preserved on large scales but tilted toward $n \rightarrow -3$ on short scales because matter fluctuations that enter the horizon in the radiation-dominated universe grow only logarithmically [3]. The division between these regimes occurs at the transition between radiation and matter domination, which corresponds to a length scale of about 13 $(\Omega_0 h^2)^{-1}$ Mpc, or a mass scale of about $3.2 \times 10^{14}(\Omega_0 h^2)^{-2} M_{\odot}$. This is where the CDM fluctuation spectrum has a "knee;" for lengths or masses larger than this, the amplitude of the fluctuations starts to fall off rapidly, approaching the primordial Zel'dovich spectrum on large length scales.

Standard CDM [4] with biased galaxy formation [5] gives an excellent account of structure formation from galaxy to cluster scales. But all the available evidence on large scale structure—from the galaxy streaming velocities, APM [6] and COSMOS [7] measurements of the galaxy angular correlation function $w_g(\theta)$, IRAS and CfA redshift surveys, radio galaxy and rich clusters data, [8] and now COBE—is pretty consistent. And this evidence suggests that a little more power is required on length scales of $\sim 10^2$ Mpc and beyond than that in the CDM fluctuation spectrum—at least, if the visible matter is related to the underlying mass distribution in a simple way [9]. CDM could perhaps be consistent with the data if galaxy formation, like the weather, is such a complicated process that it can only be described by a rather arbitrary biasing prescription [10]. But as an originator of CDM, I have always felt that one of its most attractive features is its highly predictive character. So I consider such CDM models to be non-standard, and not obviously more attractive than other CDM variants such as $\Omega = 0.2$ CDM or C+HDM, for example.

To keep the situation in perspective, it is important to note that CDM does not fail by very much. COBE [11] sees $10°$ fluctuations with rms amplitude over the whole sky of $\Delta T/T \approx 10^{-5}$. The amplitude predicted by standard CDM is $10^{-5}/b$, where the biasing factor b is as usual the inverse of the rms mass fluctuation in a sphere of radius 8 h^{-1} Mpc [12]. Thus with $b = 1$, CDM agrees with COBE, and also incidentally with much of the large scale data. However, almost all nonlinear CDM calculations agree that $b = 1$ CDM predicts galaxy velocities on small scales that are too high, while $b \approx 2.5$ does much better in this regard. Thus the problem with CDM is only about a factor of two or three. But the COBE and large scale galaxy distribution data are now so good that this sort of fudge is unacceptable! However, this near-agreement certainly does suggest that some—perhaps most—of the basic assumptions of CDM may be right. In particular, it suggests that structure grew in the universe by gravitational collapse rather than, for example, because of energy input from giant explosions: Matter fell, it wasn't pushed!

3. Hybrid models for large scale structure

Perhaps the simplest variant of CDM that remains viable has $\Omega \approx 0.2$ with $h \approx 1$ and a cosmological constant $\lambda \equiv \Lambda/3H_0^2 = 1 - \Omega$ for consistency with inflation and with CMB constraints. This model has more large scale power than standard CDM mainly because matter domination occurs later with Ω lower, so the "knee" in the power spectrum is moved to larger scales. This model is claimed to be consistent with the galaxy angular correlation function $w_g(\theta)$ [13], with the observed rich cluster correlation function $\xi_c(r)$ [14] and mass function [15], and with power spectra from clusters [16], the CfA slices and the Southern Sky redshift survey [17]. There is a possible problem in this model simultaneously fitting the large-scale peculiar velocities, which require small linear bias $b < 1$, and COBE, which requires larger b [18].

There are, moreover, several indications that $\Omega \approx 1$, for example CMB dipole vs. QDOT/IRAS data, comparison of IRAS density and galaxy peculiar velocity data, reconstructing Gaussian initial conditions from the POTENT analysis of galaxy peculiar velocity data, and void outflow [19]. While this evidence that $\Omega = 1$ is still not compelling, and the arguments for a large Hubble parameter [20] and an old universe do point toward smaller Ω, I personally am persuaded that it is likely that $\Omega = 1$.

The question arises whether *any* $\Omega = 1$ model with a physically motivated smooth spectrum of adiabatic Gaussian fluctuations can account for all the data now available, including the COBE CMB fluctuations (corresponding to scales of 3000–300 h^{-1} Mpc), large scale structure data (300–10 h^{-1} Mpc scales: galaxy angular correlations $w_g(\theta)$, the cluster correlation function $\xi_c(r)$, and galaxy streaming velocities, etc.), and smaller scale structure data (10 h^{-1} Mpc–10 h^{-1} kpc: galaxy formation, correlations, and velocities)?

One variant of standard CDM that has received much attention recently [21] keeps all the usual assumptions except the Zel'dovich primordial spectrum $|\delta_k| \propto k^n$ with $n = 1$, substituting instead "tilted" spectra with $n \approx 0.5 - 0.7$ that arise from more or less complicated inflationary models. Such models have the virtue of being very well specified, with n being the only additional parameter beyond those of standard CDM. However, it seems that "tilted" CDM is marginal at best. For example, for $n < 0.6$, sufficiently small to account for the observed large scale structure, there is probably too little early galaxy formation. Of course, it is possible to get much more general non-Zel'dovich primordial fluctuation spectra from inflation [22], but these "designer spectra" are neither well motivated nor well specified.

I will use the phrase Cold + Hot Dark Matter (C+HDM) to refer to a model with $\Omega = 1$ having roughly half as much hot (light neutrino) dark matter as cold dark matter. These proportions of hot and cold dark matter are required to fit the large-scale structure data [23]. C+HDM is physically at least as well motivated as tilted CDM or any other variant of CDM that we know. Moreover it is well specified and has only one additional parameter beyond those of standard CDM: the neutrino mass $m(\nu_\tau)$, or equivalently

$$\Omega_\nu = [m(\nu_\tau)/23\,\mathrm{eV}]h_{50}^{-2}\ , \tag{1}$$

where $h_{50}(= 2h)$ is the Hubble parameter H_0 in units of 50 km s^{-1} Mpc^{-1} [24]. The required value of $m(\nu_\tau)$, about 7 eV for $h_{50} \approx 1$, is consistent with the value implied by the currently available solar neutrino data plus the old "seesaw" models of neutrino masses, as I will discuss in §IV below. The neutrinos provide an unclustered dark matter component on small scales, which could help explain why dynamical estimates give $\Omega < 1$ on small scales. The out-of-equilibrium relativistic Fermi-Dirac statistics of the neutrinos [25] enhances this effect.

The main objection to C+HDM in principle is the apparent unliklihood of having two different dark matter components each making comparable contributions to the mass density. Although one of the earliest C+HDM papers [26] proposed a particle physics model to account for this, I am unaware of any such model that is attractive. However, the entire particle physics Standard Model begs for further explanation, so it should not disturb us to contemplate one more feature that, if valid, would call for a more fundamental justification.

Basic properties of mixed dark matter models were worked out some time ago [27]; and the fact that C+HDM with $\Omega_{cdm} \approx 0.6$ and $\Omega_\nu \approx 0.3$ is a promising model for large scale structure was established by several previous linear calculations. The C+HDM power spectrum [28] fits the data better than any other model yet proposed [29]. A simplified nonlinear calculation in a 14 Mpc box has been done with the initial neutrino fluctuations set equal to zero [30]. My colleagues and I have just done the first detailed nonlinear calculations for C+HDM, with proper initial conditions, sufficiently many hot particles to sample velocity space adequately, and a careful analysis of dark matter and galaxy correlations and velocities with comparisons to the available data [31]. We find that C+HDM normalized with linear bias factor $b = 1.5$ is consistent both with the COBE data and with the observed galaxy correlations. The number density of galaxy-mass halos is only a little smaller than for CDM at zero redshift but increasingly smaller at redshift $z > 2$, but the numbers of cluster-mass halos are slightly larger. We also find that on galaxy scales the neutrino velocities and flatter power spectrum in C+HDM result in galaxy pairwise velocities that are in good agreement with the data, and about 30% smaller than in CDM with the same biasing factor. On scales of several tens of Mpc, the C+HDM streaming velocities are considerably larger than CDM. As a result, the "cosmic Mach number" [32] in C+HDM is about a factor of two larger than in CDM, and probably in better agreement with observations.

Thus C+HDM looks promising as a model of structure formation. The presence of a hot component requires the introduction of a *single* additional parameter beyond standard CDM—$m(\nu_\tau)$ or equivalently Ω_ν —and allows this model to fit essentially *all* the available cosmological data remarkably well. One possible problem is the latest published upper limit on $\sim 1^\circ$ CBM fluctuations from the Santa Barbara South Pole experiment [33]. It has been claimed that no Gaussian model can simultaneously account for these data and the high values of the large scale galaxy streaming velocities suggested by the latest data [34]. However, only one channel of the South Pole data were analyzed, with the signal in the other three channels is interpreted as being galactic in origin [33]. It was reported at a conference in Berkeley in December 1992 that if all the data are analyzed, the result is consistent with the COBE amplitude extrapolated with a Zel'dovich primordial spectrum. Several other independent data sets apparently also show CMB fluctuations at the level predicted by C+HDM, including a newer South Pole dataset, data from the MIT and MAX balloon-borne detectors, and recent Tenerife observations.

Of the non-Gaussian models that have been proposed [35], the idea of structure formation by wakes of long cosmic strings is now perhaps the most interesting one. Cosmic strings and cosmic texture are both generic, in the sense that particle physics Lagrangians with suitable sets of scalar fields will automatically generate such topological structures in the early universe. The texture model now appears to be ruled out by the COBE data [36]. And the version of cosmic strings that was most thoroughly investigated, in which structure is seeded by small loops of cosmic string, has now been ruled out since high resolution simulations show that these loops do not survive long enough: they are quickly cut up by string crossing and reconnection.

The $\Omega = 1$ long-string-wake Strings + Hot Dark Matter model is well motivated and well specified—in fact, it has only one parameter, the mass per unit length on the string. The dark matter in this scheme is presumably hot dark matter: a τ neutrino with mass $m(\nu_\tau)$ given by Eq. 1. This (like the $m(\nu_\tau)$ needed for C+HDM) is in the range suggested by the MSW explanation of the solar neutrino data plus simple seesaw neutrino mass models. With long string wakes providing the seeds for structure formation, using hot rather than cold dark matter gives this model relatively more large scale power and is expected to suppress the formation of dense cores of dark matter in galaxies. Preliminary investigation of this scenario suggests that it might be consistent with COBE and the large scale structure data (Francois Bouchet, private communication). More detailed calculations will be required to see whether this is really true, and also whether the galaxies formed in this model have the right properties and distribution.

My sketched Figure summarizes this discussion. The three most popular models for large scale structure of the early-to-mid-1980s—HDM, CDM, and Cosmic String Loops—are now all dead and buried (at least in their simplest incarnations). Let them rest in peace! But from their graves the three leading present models are growing: CDM in an $\Omega \approx 0.2$ universe with a cosmological constant, $\Omega = 1$ C+HDM,

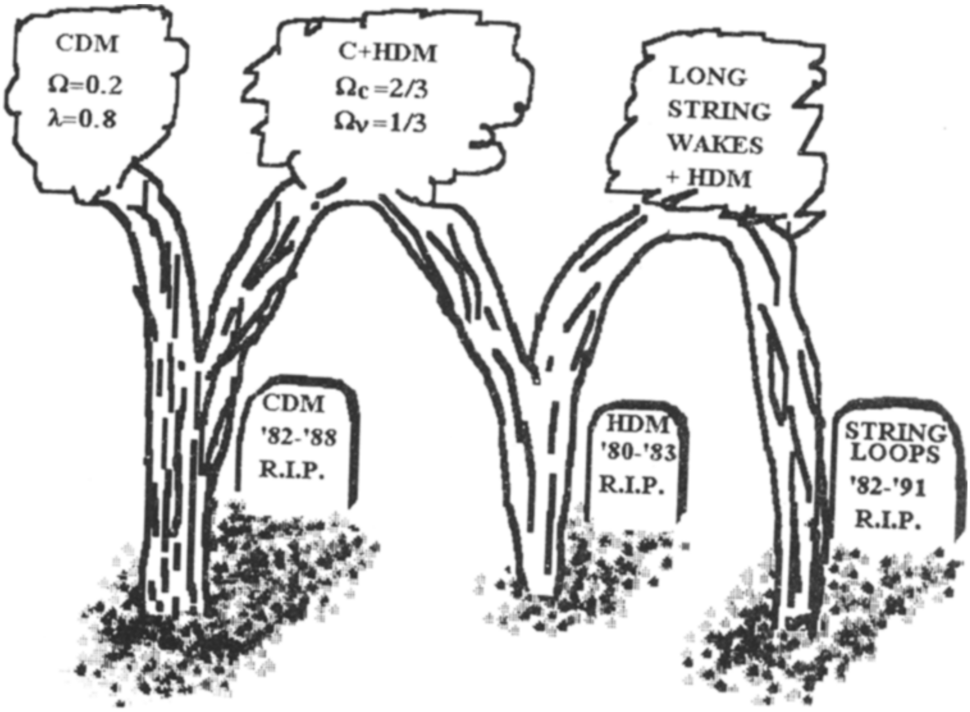

Figure 1. Standard CDM with constant linear bias b is inconsistent with the data, as is standard HDM. The idea that loops of cosmic string seed structure formation has been killed by high-resolution simulations showing that the loops do not survive long enough. But from the graves of these models potentially successful models are growing: CDM with $\Omega \approx 0.2$ and a cosmological constant, and $\Omega = 1$ Cold+Hot Dark Matter and Strings + Hot Dark Matter.

and $\Omega = 1$ String Wakes (with hot dark matter). The former two are Gaussian models consistent with cosmic inflation, the latter is a non-Gaussian model that may [37] be consistent with inflation. If measurements of the cosmological paramenters turn out to give low Ω and high $H_0 = 80 - 100$ km s^{-1} Mpc^{-1}, then the first of these models is favored. If the indications from galaxy peculiar velocities and other data that $\Omega \approx 1$ are valid, then the latter two models are favored. Of course, many other models have been proposed, and many more are possible. We have been surprised before by the data and are likely to be surprised again!

4. Solar neutrinos, neutrino masses, and hot dark matter

The GALLEX intermediate-energy solar neutrino flux of $83 \pm 19 \pm 8$ SNU is only a little less than expectated in the Standard Solar Model (SSM); and the entire SAGE dataset is not in disagreement with this. However, the high-energy solar neutrino data from Kamiokande-III and Homestake are not compatible with the SSM. The MSW neutrino-oscillation idea now seems very attractive—and certainly less ad hoc than other proposed solutions to the solar neutrino puzzle. It is interesting that it may also help explain why supernovae explode [38].

The MSW scheme requires that both the electron neutrino ν_e and at least one other neutrino—say, the muon neutrino ν_μ—have a nonvanishing mass, with $m(\nu_\mu) > m(\nu_e)$. Then the electron neutrinos emitted in the center of the sun get an effective mass $m_{\text{eff}}(\nu_e)$ because of the high electron density there. MSW also requires that $m(\nu_\mu) < m_{\text{eff}}(\nu_e)$, and that there be a nonvanishing mixing between ν_μ and ν_e, analogous to the Cabibbo mixing between the first two quark generations. Then as the ν_e's stream out of the center of the sun, $m_{\text{eff}}(\nu_e)$ decreases and eventually crosses $m(\nu_\mu)$. As usual in quantum-mechanical level crossing, the probability of conversion of ν_e into ν_μ will depend on the ν_e energy and on the neutrino mixing and masses—actually on $m(\nu_\mu)^2 - m(\nu_e)^2$. If we assume that $m(\nu_\mu) >> m(\nu_e)$, then the combined solar neutrino data favor

$$m(\nu_\mu) \approx (2-3) \times 10^{-3}\,\text{eV}, \tag{2}$$

with the $\nu_e\nu_\mu$ mixing angle $\theta_{e\mu}$ confined to two small regions, either large or small (nonadiabatic) mixing ($\sin 2\theta_{e\mu} \approx 0.8$ or 0.1).

A muon neutrino mass in this range was expected in the context of the "seesaw" mechanism for generating neutrino masses [39], in which the light left-handed neutrinos mix with heavy (mass M) right-handed Majorana neutrinos. The resulting neutrino masses are related to the squares of the masses of the upper component quarks of the same generations: $m(\nu_{e,\mu,\tau}) \approx m^2_{u,c,t}/M$ [40], so

$$m(\nu_\tau) = \eta(m_t/m_c)^2 m(\nu_\mu), \tag{3}$$

where $\eta \sim 0.3$ is a model-dependent factor including the effects of the running of coupling constants. With $m(\nu_\mu)$ of Eq. (2) from the solar neutrino data, and a top quark mass $\sim 10^2$ times that of the charmed quark, this leads to $m(\nu_\tau) \sim 10$ eV, and correspondingly to a cosmological density of τ neutrinos again given by Eq. (1). Even if the seesaw idea is right, however, it remains an assumption of simplicity that the heavy right-handed neutrinos in all three generations have the essentially the same mass M; if this is not true, then the mass estimate for $m(\nu_\tau)$ above is invalid.

Most exciting, the Chorus and Nomad $\nu_\mu\nu_\tau$ oscillation experiments now underway at CERN should see a signal within about two years if these neutrino mass and mixing models are right (§V below).

To summarize: the very plausible MSW explanation of the solar neutrino data requires neutrino mass, and thereby goes beyond the Standard Model of particle physics. And the combination of that, together with the admittedly rather speculative seesaw model of neutrino masses with a single intermediate mass scale M, leads to the prediction that light τ neutrinos—hot dark matter—may be all or at least a considerable fraction of the dark matter.

5. Dark matter detection

5.1. Light neutrinos—new neutrino oscillation experiments

These speculations about neutrino masses can be tested by experiments now underway at CERN, and also by using the next generation of solar neutrino detectors, including Super-Kamiokande and Sudbury Neutrino Observatory, to clarify the energy-dependence and generational composition of the solar neutrinos reaching the earth. By measuring the energy spectrum of high energy solar neutrinos using both charged and neutral current interactions, these experiments can help determine whether the MSW model can explain the data, and if so for which values of muon neutrino mass and $\nu_e\nu_\mu$ mixing angle.

Because they are less well known than the solar neutrino experiments, I will describe here in a little more detail the new $\nu_\mu\nu_\tau$ oscillation experiments now being built at CERN. In the Chorus experiment (CERN-WA-095, approved September 1991), a beam of muon neutrinos produced by the proton beam of the CERN-SPS accelerator are directed at a target consisting of nearly a ton of nuclear emulsion stacks. If $m(\nu_\tau)$ lies in the cosmologically interesting range from a few eV to $\sim 10^2$ eV and the $\nu_\mu\nu_\tau$ mixing angle θ satisfies $\sin^2 2\theta \gtrsim 3 \times 10^{-4}$, then a substantial number of ν_μ will oscillate to ν_τ on their way to the detector. The emulsion stack will then capture the ~ 1 mm tracks of the relativistic τ leptons produced by $\nu_\tau+$ nucleon $\rightarrow \tau^- + X$, thereby providing the first direct evidence for the τ lepton as well as a measurement of its mass and of θ. The hard part is finding the tracks! They are to be located by a combination of techniques, including scintillating fiber trackers, a layer of emulsion that is changed biweekly, and a calorimeter that tags the τ^- decay by its transverse momentum imbalance. The complementary Nomad experiment (CERN-WA-096, also approved September 1991) looks for τ production from the ν_μ beam in a 3 ton drift chamber target by a magnetic detector based on the old CERN UA1 magnet. It searches for the various decay modes of the τ using kinematical criteria, and has roughly the same sensitivity as Chorus.

Are these experiments sensitive enough? Yes, if the $\nu_\mu\nu_\tau$ mixing angle θ is comparable to the corresponding quark mixing angle $\theta_{23} \approx 0.04 \pm 0.01$, which would imply $\sin^2 2\theta \gtrsim$ few $\times 10^{-3}$. Several particle physics models of neutrino masses and mixings also suggest that Chorus and Nomad may be sensitive enough [40]. But even if θ is too small for τs from $\nu_\mu\nu_\tau$ oscillations to be seen in these CERN experiments, all is not lost: an emulsion experiment similar to Chorus has been proposed at Fermilab that will be an order of magnitude more sensitive after the injector upgrade has been completed. Thus it seems quite likely that if $m(\nu_\tau)$ is in the range required for Cold + Hot Dark Matter or Strings + Hot Dark Matter models, this will soon be confirmed by accelerator experiments.

5.2. WIMPs and axions

The cold dark matter particle candidates that are well-motivated (in the sense that they have been proposed for good particle-physics reasons independent of their possible cosmological properties) are axions, still the best solution to the strong-CP problem, and weakly interacting massive particles (WIMPs), in particular the lightest supersymmetric partner particle (LSP). Both are detectable in the laboratory [41].

WIMPs that form the halo of our galaxy have an rms speed of about $v = 300$ km s^{-1} $= 10^{-3}c$ (a little higher than the 220 km s^{-1} orbital speed of the sun in the galactic disk, since the velocity of halo matter should be essentially isotropic). Thus a WIMP of mass m has kinetic energy $\frac{1}{2}mv^2 = \frac{1}{2}(mc^2/\text{Gev})$ keV, which can be transferred as recoil energy to a nucleus in a target in the laboratory. The probability of such interactions is of course determined by the collision cross section;

non-detection of such events by ionization detectors has already excluded large-cross-section WIMPs such as massive Dirac neutrinos for a large range of masses. A typical event rate for allowed LSP WIMP dark matter particles is of the order of an event per kg of target material per day, so the problems are to have a large enough target to get a decent event rate, and then to distinguish these dark matter events from various backgrounds. The group associated with the Center for Particle Astrophysics at Berkeley has demonstrated the efficacy of background rejection by simultaneous detection of ionization and phonons from the nuclear recoil in a germanium detector at a few millidegrees K. (Nuclear recoil produces a weaker ionization but a stronger phonon signal, while the energy distribution is just the opposite for the main background, electron recoil from Compton scattering.) Other groups are pursuing other approaches. It is clear that detection of WIMP dark matter will be hard, but it does appear to be technologically feasible. In a few years, experiments will either have discovered the dark matter WIMP or ruled out a significant part of the possible parameter space.

Axion searches attempt to detect the conversion of axions, expected to have rest mass about 10^{-5} eV, into photons of the same energy in a strong magnetic field. (Despite their low mass, axions are cold rather than hot dark matter since they form as a non-thermal vacuum condensate.) Such searches have been conducted both at Brookhaven National Laboratory and at the University of Florida, but their sensitivity was about two orders of magnitude too low to detect the predicted axion density. The detection probability goes as the volume times the square of the magnetic field, so the availability of a large powerful magnet at Livermore National Laboratory should permit a search with sufficient sensitivity to detect axion dark matter or rule out essentially the entire expected mass range, at least for some models.

5.3. Searching for MACHOs by microlensing

It is possibile that at least a fraction of the dark matter in galaxy halos consists of some sort of astrophysical objects. One possibility is that most of the ordinary matter in the Universe may have been processed through a first generation of "Population III" stars. Dark remnants of these objects have been termed "Massive Astrophysical Compact Halo Objects" (MACHOs) by Kim Griest.

What form might the MACHOs take? A variety of constraints suggests that they might either be black hole remnants of a population of "Very Massive Objects" (VMOs) larger than 100 $M_\odot$ that collapse entirely without ejecta during their oxygen burning stage, or else objects that are too small to burn hydrogen at all (brown dwarfs or jupiters). It is also possible that they are primordial black holes.

If the MACHOs are VMO remnants, they would have two important observational signatures: a background of gravitational radiation generated by the black hole collapses and a background of electromagnetic radiation generated by the VMOs' nuclear-burning phase. The gravitational radiation may be detectable when laser interferometers go on the air in the mid-1990s (see §VI below), but this depends on the very uncertain efficiency with which collapsing VMOs produce gravitational waves. The electromagnetic radiation background might peak at 10 microns, where it would be hidden by zodiacal light; or it could have been reprocessed by dust scattering, in which case it would produce near-infrared spectral distortions that the DIRBE instrument on COBE could observe, anticorrelated in angle with submillimeter CMB fluctuations [42].

The most interesting observational consequence of jupiters would be their gravitational microlensing effects. Lensing occurs because light is bent in a gravitational field. There are two distinct effects. "Macrolensing" occurs when the light from a distant object like a quasar is bent by the gravity of an intervening galaxy or cluster to produce multiple images. "Microlensing" occurs at similar cosmological distances when an individual halo object traverses one of the macrolensed images, thereby causing its brightness to vary relative to the other images. This is only detectable at cosmological distances for halo objects in the mass range below 0.1 $M_\odot$ because the timescale of the fluctuation increases as the square root of the deflector mass and exceeds an astronomer's lifetime above 0.1 $M_\odot$. One can therefore use this effect to look for jupiters but not VMO remnants. In fact, there is already one claimed case of microlensing of a quasar [43], with the deflector mass in the range 0.001 - 0.1 $M_\odot$. However, in this case the optical depth for microlensing was probably greater than unity along the light path through the center of the lensing galaxy, which makes the deduction of the deflector mass uncertain. Also, near a galaxy center the most likely deflectors are ordinary matter rather than MACHOs.

The most promising approach appears to be to seek microlensing by MACHOs in our own Galactic halo by looking for intensity variations of stars in the Large Magellanic Cloud (LMC) [44]. In this case the timescale of the variation is shorter, about a week for a lensing object of 0.1 $M_\odot$. It again varies as the square root of the microlensing mass, so that it would be practical to look for black hole remnants from VMOs as well as jupiters. However, the probability of a particular star being microlensed is only $\sim 10^{-6}$, so one therefore has to look repeatedly at many stars.

Three groups have initiated searches for local microlensing. A group of French astronomers and particle physicists has analysed Schmidt telescope plates of the LMC, several hundred of which are presently available, half taken since supernova 1987A. Both they and the Berkeley-Livermore-Mt. Stromlo (Australia) collaboration are also repeatedly imaging the LMC with CCD cameras on dedicated telescopes in the Southern Hemisphere. A Polish group is searching for microlensing of stars in bulge of the Milky Way. Since microlensing events with light amplification factor A are distributed uniformly in A^{-1} (which is proportional to the distance of closest approach of the lensing object to the line of sight to the lensed star), the large-A events that will provide the most convincing signal should not be that uncommon. But large-A events have short duration, and the requirement of frequent sampling favors the CCD approach over plates in searching for jupiters. The fact that the increase in a star's brightness due to microlensing is independent of wavelength should help to distinguish lensing events from intrinsic stellar variations, in which the color usually changes with brightness. Preliminary results from all three groups show that the backgrounds appear to be managable; no microlensing events have yet been found.

6. Conclusion

This is certainly a golden age for cosmology and particle astrophysics! We are blessed with wonderful astronomical instruments and accelerator experiments that each year open new windows through which we see things that clarify the initial conditions, the composition, and the evolution of the universe. The fact that the ν_e-ν_μ oscillation experiments now starting at CERN may confirm the prediction of Cold+Hot Dark Matter that $m(\nu_\tau) \sim 7h_{50}^2$ eV, or perhaps that of Strings+HDM that $m(\nu_\tau) \sim 23h_{50}^2$ eV, is a perfect illustration of the interconnections growing between cosmology and particle physics.

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Discussion

R.K. Parui : What do the COBE results predict about the number of our universe, i.e., whether we live in a single or multi universe system?

J. Primack : This question can be addressed after we have enough data to begin to test inflationary theories. As I discussed, we are just beginning to acquire data on CMB fluctuations on small angular scales. Maybe in a few years we can begin to consider the early stages of inflation, or what preceeded inflation, after we have this data. Of course, theorists are free to work at such theories now.

Krishna Kumar : What is the precision of the 7 eV m_{ν_τ} prediction?

J. Primack : $\Omega_\nu = m_\nu/(23 \text{ eV})$ for $H_0 = 50$ Km s^{-1} Mpc^{-1}, and if the age of the universe is $t_0 \geq 13$ Gy, then $\Omega = 1$ requires $H_0 \leq 50$. If $\Omega \gtrsim 0.50$, there is too little early galaxly formation. If $\Omega_\nu \lesssim 0.20$, the small and large-scale velocities are too much like CDM. Thus, roughly, the C+HDM model requires $m_\nu \simeq 7 \pm 2$ eV.

R. Raja : Does your CDM + HDM model predict "gut attraction + voids"? Have you done simulations?

J. Primack : Yes, and yes. The fact that the large-scale velocities, predicted by C+HDM, agree so well with the observations shows this. All the last several plots I showed are based on elaborate simulations and in response to this question I showed more simulation results demonstrating that C+HDM produces large superdusters and voids.

A. Khare : All your discussions seem to crucially depend on assuming that $H_0 =$ 50 in appropriate units. How well one know that H_0 is 50 Km s^{-1} Mpc^{-1}?

J. Primack : We do <u>not</u> know whether $H_0 = 50$ or perhaps ~ 100. That is why I discussed two different models in detail, C+HDM with $\Omega = 1$ and H = 50 and low-Ω CDM with H $\approx$ 100.